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Published in:
Philosophical Transactions of the Royal Society A - Mathematical Physical and Engineering Sciences

DOI:
10.1098/rsta.2018.0106

Publication date:
2018

Advances in risk assessment for climate change adaptation policy

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Abstract: Climate change risk assessment involves formal analysis of the consequences, likelihoods and responses to the impacts of climate change and the options for addressing these under societal constraints. Conventional approaches to risk assessment are challenged by the significant temporal and spatial dynamics of climate change; by the amplification of risks through societal preferences and values; and through the interaction of multiple risk factors. This paper introduces the theme issue by reviewing the current practice and frontiers of climate change risk assessment, with specific emphasis on the development of adaptation policy that aims to manage those risks. These frontiers include integrated assessments, dealing with climate risks across borders and scales, addressing systemic risks, and innovative co-production methods to prioritize solutions to climate challenges with decision-makers. By reviewing recent developments in the use of largescale risk assessment for adaptation policy-making, we suggest a forward-looking research agenda to meet ongoing strategic policy requirements in local, national and international contexts.

1. Climate change challenges and the role of risk assessment

Climate change is a major challenge to society and to the ability of individual and collective decision-making to enact meaningful responses. In many senses, it is unlike other environmental problems facing humanity in its temporal scale and in its complex relationship between human agency, embedded social structures and emerging environmental system interactions [1]. In economic terms, climate change represents what Nick Stern [2] refers to as the greatest market failure the world has ever seen. Ross Garnaut suggested that failing to adequately deal with the consequences of climate change 'would haunt humanity till the end of time' [3, p. 597].

Climate change creates cascading risks in physical systems, ecosystems, economy and society, often inter-related and creating the circumstances for irreversible and undesirable crossing of thresholds at multiple scales. To assess climate risks across domains, and in a manner meaningful to decision-makers, is therefore a major scientific challenge.

Hence the scientific and analytical approach to the climate change challenge requires the inclusion of systematic complexity and the ability to incorporate perhaps normally unthinkable and non-obvious elements to decision-oriented framing. At the same time, policy-makers are under pressure to make decisions on climate change which intersect with many other policy domains and have both immediate, short-term consequences and perhaps more profound, long-term implications. This includes decisions on mitigation strategies to reduce greenhouse gas emissions and climate change forcing, and on adaptation strategies which aim to manage existing and future effects of climate change that are unavoidable, and which are the primary policy focus for this theme issue. This issue brings together multiple perspectives on large-scale climate change risk assessment to investigate challenges in the use of risk-based concepts and expert assessment as well as the management of uncertainty over different time scales.

At its simplest, the object of risk analysis concerns the loss or gain of something of value, and is most commonly associated with the consequences of an action or event multiplied by its likelihood. Risk framing incorporates, however, multiple dimensions of the societal context of decision-making such that, while some risks are observable, or emergent for interactions in the physical world, other risks include indirect, systemic ones or relate to collective and political systems rather than to individuals.

Risk assessment involves both formal methods and processes to delineate and evaluate risks, through to everyday practices of how individuals act, from trivial decisions of wearing a coat when there is a probability of rain, through to major decisions on where people live, move or invest their resources. Risk assessment, in general, is a process to comprehend the nature and to determine the level of risk [4]. Importantly, any risk assessment is purposeful, most often conducted to inform a particular type of decision and action. This usually requires the measurement of risk—facilitating a comparison between different risks and an understanding of possible impacts, often presented through models or scenarios. Risk assessment has, therefore, become institutionalized as common practice in government, business and other organizations, to guide actions based upon an evaluation of their consequences accompanied by prioritization of measures to reduce downside and negative consequences (e.g. [5]). Risk science is particularly evident in the context of disaster, where growing understanding of the interplay between hazard, vulnerability and exposure has led to ever more comprehensive and sophisticated risk models and assessment methods [6].

In government, many policy-making decisions are concerned with risk management and prioritization through the development of standard rules and guidance to reduce the prospect for adverse consequences. As the landscape of risks evolves due to macro-scale drivers of change, such as urbanization, economic development and land-use changes and other emergent factors, scientific advice can be crucial to rationalize these based upon current knowledge, and, if there are competing interpretations of risk, to explain why in the clearest possible terms [7].

There are two important social elements of risk pertinent for risk assessment. The first is the so-called social amplification of risk, whereby responses to perceived outcomes, either in anticipation or in reaction, change the landscape of likelihood or consequence. In other words, reactions such as aversion, fear or greed will affect both the likelihood and the distribution of consequences in society. Second, consequences of loss of legitimacy or control are central to institutional or political risks: these types of risks affect what is defined as downside risk and where efforts are made in response. The lessons from decades of analysis and experience of risk are, therefore, that risks are neither neutral nor fixed [8].

Risk assessment based on a reductive approach to risk was designed for familiar systems and well-defined issues; it has been shown to be less appropriate under conditions of uncertainty, ambiguity and ignorance, when reduction to a single risk metric or policy recommendation cannot be scientifically justified [9–12].

Furthermore, traditional risk assessment has been based on historic data—assessing probabilities of severity, frequency and impact based on experience from past events. In times of global change, this approach is no longer adequate to capture future risks. Furthermore, in a decision-making context, inherent uncertainty associated with climate change has been used to show that a conventional 'predict then act' framing is paralysed by limits to prediction, whereas an 'assess risk of policy' framing can act as a better stimulus for action by showing where existing policy objectives may be threatened [13]. Limitations of a reductive approach to risk also become apparent when comparative risk assessment is used as a form of evidence synthesis, across diverse evidence sources.

Risk registers aim to rank by severity and present risk dimensions in visual format, typically using a two-axes graph of likelihood and impact. At country level, national risk registers are, therefore, seen as important developments that aim to synthesize, rank and communicate multiple threats to national security [14]. Critiques of such risk-ranking approaches have recognized their utility for risk governance, especially by increasing the profile of severe and emerging issues, but also highlighted the need for better characterization of risks and issues associated with differential coping potentials [14,15]. Challenges also remain in integrating all relevant evidence and effectively communicating uncertainty in risk assessments to decisionmakers rather than conflating it within an apparent objective measure of probabilistic likelihood of an event [12].

Risk is therefore a complex and dynamic concept, multi-facetted and continuously changing, with new risk emerging constantly in a time of growing interdependencies [16,17]. The role of risk science in addressing complex global problems, therefore, continues to be refined as concepts and approaches are re-defined to address new challenges. Key issues in risk assessment are whether uncertainties in evaluation of likelihood or consequences can be reduced; whether reducing uncertainties actually leads to more effective decision-making; whether accuracy is necessary for adaptation; and whether systemic elements can be incorporated where the risks are potentially unforeseen or unknowable.

Uncertainty is an inherent feature of risk assessment, and its treatment and communication have received significant interest in the literature, as highlighted by the earlier *Phil. Trans. R. Soc. A* theme issue 'Responding and adapting to climate change: uncertainty as knowledge' [18]. Indeed, much fundamental climate science has sought to reduce uncertainties around the parameters of future changes. Cox *et al*. [19], for example, attempt to quantify climate sensitivity for a doubling of atmospheric CO_2 and derive likelihoods for the lower bound (less than 3% for 1.5°C) and upper bound (less than 1% for 4°C) ranges. They argue that knowing these likelihoods for best and worst-case scenarios is important for strategic decision-making. By contrast, Dessai *et al*. [20] argue that accurate prediction of climate is not an impediment to adaptation decision-making, and that robust adaptation requires actions that meet evaluation criteria (such as effectiveness and fairness), whatever the plausible range of future climatic changes. They show that risk assessment requires high predictive skill when there are limited alternatives and when the outcomes are known and well constrained. For many adaptation decisions, such conditions do not hold: there are numerous options, uncertainties are large and decision-makers may not have experience in using such predictions [20]. Hence risk assessment is not simply about better prediction of likelihood or consequence. Moreover, reducing uncertainties is only one means by which progress towards adaptation occurs.

2. Current practice in climate change risk assessment

Given the diversity of approaches and the complexity of risk assessment, many public bodies with statutory obligations and private bodies with responsibility to shareholders have implemented formal risk assessments of climate change impacts. Across the spectrum of experience, they frame and prioritize climate change risks alongside other risks in order to implement timely responses. At the level of global public concern, the Intergovernmental Panel on Climate Change (IPCC) have described the advantages of a risk-based approach in terms of improved understanding of both the dynamic interactions of risk factors (spatial and temporal) that lead to specific climate change impacts, and the role of adaptation initiatives in managing these risk factors. Both the Special Report on Extreme Events [21] and the Fifth Assessment Report [22] sought to characterize key global risks linked to current policy responses to provide recommendations for further intergovernmental action [23]. Similarly, risk assessment has also been highlighted as a key procedure at national scale to facilitate targeted adaptation strategies and coordinated risk governance (e.g. USA [24]).

The IPCC's Special Report on Extreme Events [21] brought together the different schools of thought that had emerged under disaster risk management and climate change adaptation by including science from both fields. The report challenged the prevailing approach of assessing risks without considering the dynamic socio-economic aspects that drive exposure and vulnerability [21]. The resulting climate risk framework has become the basis for a new generation of climate change risk assessments that are explicit about the underlying and structural nature of vulnerability. As a further development, climate risk-based approaches are also now being further integrated with disaster risk reduction concepts as complementary initiatives to develop proactive strategies for managing extreme events [25].

Cumulative risks at national and global level are also linked to discourse on the key principle of avoiding dangerous climate change as defined by the UN Framework Convention on Climate Change (UNFCCC) [26]. This principle is now strongly attached to assumed risk thresholds of +1.5°C and +2°C global warming above pre-industrial level as defined by the 2015 UNFCCC Paris Accord to provide the rationale for complementary adaptation and mitigation actions. Risk assessment at higher magnitudes of climate change has also identified the additional consequences from exceeding these thresholds, notably the scale of disruption associated with a benchmark +4°C global warming above pre-industrial, which remains a possibility under 'business as usual' greenhouse gas emissions [27].

The importance of climate change risk assessments is recognized politically through the existing global frameworks that attempt to lead global action: the United Nations Framework Convention on Climate Change (UNFCCC) and its Warsaw International Mechanism for Loss and Damage (L&D) as well as the Sendai Framework for Disaster Risk Reduction (SFDRR), coordinated by the United Nations Office for Disaster Risk Reduction (UNISDR), all underline the importance of evidence-based risk assessment to guide public policy.

However, the complexity of climate change suggests that it is not the type of well-defined problem suited to conventional risk assessment, and IPCC report procedures have evolved in the face of this challenge [28]. Hence, innovations in risk methodology and communication have been developed, sometimes drawing on parallel developments to address other wicked problems [29–31]. For example, a now familiar technique is the development and application of scenarios for climate change assessments to represent diverse future pathways beyond the range of conventional prediction techniques or probabilistic likelihoods used in conventional risk assessments. A perhaps more radical innovation for risk assessment is to recognize that much uncertainty in climate change assessments is irreducible and to treat this not as a barrier but as a source of 'actionable knowledge' through its influence on the viability of different decision strategies [32]. A further development is to recognize that climate change may also provide opportunities, and hence to position risk assessment as a mechanism to evaluate both positive and negative aspects of change in the context of a balanced appraisal of alternative decision options.

3. Overview of contributing articles

This collection of papers examines different approaches to climate risk assessment across the natural and social domains, with a special focus on how they can inform interventions and plans to minimize and manage the risks. The papers offer new insights into the multi-scalar and nested nature of risk assessment, drawing on global risks that become meaningful to decisionmakers at national and local scales. Distinctive challenges can, therefore, be identified in linking the strategic needs of adaptation policy with the evolving science of risk and across the many academic disciplines contributing to climate change science.

Many of the papers in this theme issue build on experience of the UK Climate Change Risk Assessment (UKCCRA) [33] as well as international expertise in national level risk assessments, focusing on the methodological advancements and challenges recently experienced.

Warren *et al*. [34] evaluate developments in the UKCCRA methodology. The origins of the UKCCRA were linked to aspirations to include climate change risks on a National Risk Register. The first assessment completed in 2012 was criticized by some commentators for being overtechnical, as exemplified by use of risk metrics to quantify changing risk profiles which were more suited for some risks compared to others. Hence, Warren *et al*. [34] describe how the methodology was refined for the second assessment completed in 2017, including assessment of both present-day and future vulnerability, and provide a focus on the urgency of adaptation action and a structure focused around systems of receptors rather than conventional sectors. The methodological changes reflect an evolution from a 'science-first' assessment to a 'policy-first' assessment to provide improved relevance to adaptation policy. Procedures are, therefore, more action-oriented than the IPCC reporting process.

Sectoral or quasi-sectoral experience with climate change risk assessment offer insights into application and methodological challenges that researchers and policy-makers face when conducting national climate risk assessments. Dawson *et al*. [35] evaluate climate risks across UK infrastructure sectors through a systems approach. They find that the understanding of risks to individual infrastructure sectors has improved but is still lagging for risks from interconnectivities and interdependencies.

Brown [36] describes how an ecosystem-based approach was used to assess risks for the natural environment and its multiple societal benefits. The challenge here is related not only to establishing consistency and hence priorities across diverse systems and receptors but also to understanding the nature of risk related to objectives and hence the rationale for adaptation policy.

Surminski *et al*. [37] investigate climate risks across the wide diversity of business interests and industry sectors, identifying several methodological challenges for incorporating these into national-level climate risk assessments, most notably the diverse nature of evidence, interdependencies across value chains and business relationships, and the impact of policy and regulation.

A key methodological advancement of UKCCRA2 is the recognition of the international dimension of climate risk and adaptation policy. Challinor *et al*. [38] explore this in the context of risk transmission across international boundaries, which are linked to mechanisms such as price, material flows, movement of people and political stability, with specific emphasis on food security and geopolitical risks.

The experiences from the UKCCRA process are complemented by two national-level perspectives for Italy and Mexico, showcasing methodologies and challenges of applying risk assessments across scales: Mysiak *et al*. [39] describes the climate risk index for Italy, which was initially developed to inform the National Climate Adaptation Plan in Italy and offers improvements in the underlying assessment methods through more detailed model ensemble data and a more robust analysis. The results of the analysis are used to rank the subnational administrative and statistical units according to the climate risk challenges, and inform financial resource allocation for climate adaptation in Italy.

Haer *et al*. [40] conduct a country-scale study of future flood risk in Mexico, illustrating how the application of global models can inform cost–benefit analyses to prioritize investments in flood adaptation strategies under future climate scenarios in data-scarce countries. The methodology applied here is particularly relevant because local data are often lacking, incomplete or inconsistent.

The collection of papers concludes with reflections on the application of risk assessment: McDermott & Surminski [41] explore the challenges of translating risk assessment into action at the local city level. Their exploratory study at city scale in Cork, Ireland, shows how normative interpretations of climate risk assessment affect local decision-making, highlighting that, despite ever more accurate data and an increasing range of theoretical approaches available to local decision-makers, there are fundamental challenges that can hamper action.

The concluding commentary from Brown *et al*. [42] is written from the perspective of the Climate Change Committee, which oversees the UKCCRA and provides independent guidance to the UK government on policy development. The authors describe how the UKCCRA has acted as a primer for research and knowledge exchange across the science–policy interface, and outline how the utilization of the risk assessment could be improved further.

4. Future directions for risk assessment

The contributions to this theme issue and the wider emerging science of risk assessment point to a number of frontier issues relevant for assessing the risks associated with climate change in a policy-based context. These include the issue of dealing with systemic risks, together with critical knowledge gaps regarding biophysical and Earth system processes, and the complexity of societal responses, which could collectively lead to extremely challenging outcomes. Other issues relate to risk assessment processes themselves, such as dealing with uncertainty or managing the diversity of evidence. And finally, the interplay between adaptation action, policy and risk levels is not well understood and requires further investigation. We reflect on each in turn and identify possible responses.

The first challenge in risk assessment for global climate change is undoubtedly the *complexity and myriad of interacting factors*. For every incremental change in greenhouse gases and temperature, there are diverse responses in climatological, ecological, hydrological and other biophysical systems, ranging from short-term effects on primary productivity, through to longer-term changes such as sea-level rise, weathering or soil formation; coupling of systems means that responses also affect other systems, including feedbacks to climate. In addition, climate change risks are shaped by complex interactions with socio-economic drivers, together with individual or collective responses to risk through planned and more reactive adaptation. All these interactions indicate high propensity for indirect effects and systemic risks that cascade through multiple receptors, especially during and following extreme events. Advances in attribution of extreme events allow greater identification of where individual events have moved into the realm of anthropogenic climate change, and methods in specific areas of hydrology and meteorology are improving risk profiling through assessments of changes in event magnitude and frequency (e.g. [43]). But the key challenge is to identify how systemic risks cascade through interdependent networks, including for infrastructure, businesses, vulnerable communities, ecosystems and ecosystem services.

There is now also increased recognition of systemic risks extending beyond national jurisdictions, but accompanying concerns regarding rather limited information on their structure and potential consequences [16]. As Challinor *et al*. [38] argue, the presence of political boundaries across natural systems such as seas and watersheds represent a barrier, and sometimes an amplification of risks.

Conventional risk assessment methods, and indeed other policy appraisal tools, are ill-equipped to deal with interaction effects, and with multiple time scales. In this theme issue, there are a range of new perspectives on how to assess these interdependencies and interactions, for example, Dawson *et al.*'s systems approach for infrastructure [35], the business-function framework for risks to industry and business applied by Surminski *et al*. [37], and the risk transmission framing in Challinor *et al*. [38] showcase methodological advances. However, they all also conclude that further interdisciplinary advances in integrated assessment approaches that link dynamic biophysical and socio-economic components of risk exposure and vulnerability are required (see also [44]). Similarly, Brown [36] suggests a key step towards a better understanding of these interactions is to use system thinking and sensitivity testing to identify key linkages and the potential for critical transitions, including the role of humans as modifying agents for terrestrial, freshwater, coastal and marine ecosystems. By engaging with practitioners, risk assessment can not only include their valuable specialist knowledge, but also map out the transmission of risk across sectors and scales, recognizing also that complete avoidance of risk is probably unviable and impracticable.

Interaction of climate with a variety of processes of global environmental change represents an increased need for methodological triangulation to identify and characterize multiple stressors and their interactions across different scales [45]. This will require further innovations in scenario development to incorporate coevolution of drivers, for example, using the IPCC Shared Socioeconomic Pathways (SSP) framework [46] at national and regional scale, and the incorporation of empirical data into attribution frameworks using innovative techniques such as data pooling over large areas to discriminate confounding factors. A methodological shift for risk assessment can also be witnessed in approaches allowing greater reflection on the social construction of risk and how this influences vulnerability and exposure. Tools such as agent-based models or qualitative investigations of human behaviour can help to capture those dynamics, but their inclusion into climate risk assessment models is still underdeveloped [47]. While risk science has become more inter-disciplinary, embracing the skills and knowledge gained in the social sciences, there is a strong call for more efforts to improve analytics and make this more applicable to decision-makers.

Unknown Earth system responses and unknowable future societal responses lead in effect to deep uncertainty within climate change risk assessment. In the face of this deep uncertainty, there are a number of potential strategies. These include the need to portray a full range of extreme future scenarios, and being explicit concerning the possible goals of adaptation responses [48].

The second challenge to climate risk assessment stems from the *diversity of evidence and varieties in underlying assumptions*, in the use of scenarios, and in the prior questions of determining the scope of assessment. One of the main bottlenecks in understanding risk dynamics is limited availability and relevance of existing data. This is a challenge identified by all papers, but it can also be an opportunity for innovation, as shown by Haer *et al*. [40], who test the application of global datasets to run national and state-level risk assessments in Mexico as a possible way to circumvent data-scarcity. A similar comment applies to Mysiak *et al*.'s [39] climate risk index for Italy.

Importantly, despite any advances in risk quantification, expert judgement remains at the heart of assessment: to evaluate different evidence sources, establish the degree of scientific consensus and communicate confidence levels. A challenge noted in several papers in this theme issue and from the US National Assessment [49] has been to develop a consistent framing of risk and treatment of uncertainties across multiple stressors and receptors. Particularly for highly contested issues, there remains scope for further development of structured evidence appraisals, such as by pedigree and uncertainty assessment [50]. Such refinements are especially necessary due to the potential contestation of climate change actions which makes it important that risk assessment can show a transparent audit trail that cautiously and rigorously justifies the interpretation of scientific evidence, particularly when model-based results are involved [51,52].

All formal climate change risk assessments are structured by underlying values and normative goals that are sometimes explicit and sometimes hidden. These values include societal attitudes to the intrinsic value of nature, through to collective aversion to loss and dread, irreversibility, as well as implicit judgements on the acceptability or aversion to inequality in society. Climate risks associated with land use, for example, are dramatically different when agricultural policy incentives prioritize food production over environmental protection, as evidenced in land management in the UK contributing significantly to lowland flood risk [53]. These trade-offs may lead to maladaptation as uncoordinated responses to climate change exacerbate risk, as Brown [36] identified for different types of ecosystem services. Barnett *et al*. [54], for example, highlight how individuals are averse to irreversible loss, and these are often articulated through attachment to places, to iconic artefacts or other representations of culture. Hence formal risk assessment can deviate from making meaningful statements on priorities, when these normative goals fail to be recognized. Even in situations where data are available and presented to decision-makers, as in the Cork example provided by McDermott & Surminski [41], it is important to understand the underlying assumptions and limitations of a risk assessment. This requires transparency and close engagement between those who conduct the risk assessment and those who commission or use it [42].

The third frontier area is that of *uncertainty management* to support science–policy interactions. Uncertainty management is crucial to further developments across the science–policy interface. Conventional appraisal procedures used for policy decisions (e.g. cost–benefit analysis) have been shown to have a tendency to close down too rapidly to a small set of options by defining uncertainty too narrowly [55]. In climate change policy, an adaptation deficit can be defined in terms of the gap between residual risks that are intolerable for society and current adaptation responses. However, the presence of irreducible or deep uncertainty identifies that such a gap should not be seen as just a knowledge deficit issue which may be associated with a 'wait and see' or incremental response. Instead, developments in risk science suggest that deep uncertainty needs to be recognized through innovative procedures and actions that are more participatory, risk-informed and precautionary in response, rather than following a conventional risk-based approach based upon reductive metrics and decision trees [56,57]. Innovative use of risk and uncertainty concepts in adaptation decision-making is now under way, requiring further development and application, such as the use of risk layering matched to different magnitudes of risk and their return periods [58], or the use of stress testing to assess critical natural capital required to maintain ecosystem services [59], or the use of robust decision-making and dynamic adaptation pathways linked to trigger points that incorporate different prospective rates of climate change [60,61].

The fourth area relates to how *current and planned policies and adaptation actions* mediate climate risks, including the relations between adaptation policy aspirations, present adaptation action and adaptive capacity. The inclusion of adaptation action was a specific requirement for UKCCRA2, arguing that after several years of adaptation planning and policy-making it could be expected to see certain changes in adaptive behaviour that would in turn influence risk levels [34,42]. Evidence on adaptation is emerging, as shown for infrastructure [35] and for business and industry [37], but this is mostly in a descriptive anecdotal rather than quantifiable or comparable form. Stakeholder engagement in the risk assessment process to generate at least anecdotal evidence and to collect views on adaptive capacity and barriers to action are important steps that can be taken in the absence of comprehensive adaptation data, but it limits the policy conclusions that can be drawn. Therefore, methodological advances to characterize adaptive capacity across different sectors as well as improved data collection and data sharing exercises are essential. Brown [36] also argues that for the natural environment we need a better characterization of natural adaptive capacity, and hence how climate resilience can be enhanced through linking human adaptation with natural adaptation processes.

Another consistent conclusion from papers in this theme issue is the need for a more rigorous incorporation of adaptation effectiveness within risk assessments. This includes the viability of different adaptation processes (including reactive or proactive responses), for successfully addressing current and future climate change, together with sensitivity of their desired outcomes to irreducible uncertainty. Monitoring and evaluation data on adaptation are often lacking or extrapolated from small surveys or information from early adopters [62]. In addition, the variety and complexity of adaptation processes mean that the current generation of integrated assessment models, which are otherwise useful for understanding combined future climate and socioeconomic impacts, have been shown to be rather deficient in explicating the role of adaptation in mediating risks [63]. Risk assessment also requires better information on lead times required for converting policy aspiration into policy implementation, as such translation may be impeded or delayed by institutional or societal barriers [64], with implications for defining residual risks and the limits to adaptation, especially at higher magnitudes of climate change [28,65]. Understanding of response capacities also needs to extend in scope to investigate how prospects for better integration of adaptation and mitigation agendas may provide complementary initiatives to manage climate change risk in practice [66].

Finally, this theme issue provides insights on the challenges of *applying risk assessments for adaptation decision-making.* As seen in the UKCCRA context, there is a clear expectation from decision-makers in terms of applicability of the risk assessment, as highlighted by Brown *et al*. [42], who argue that 'the next CCRA, due in 2022, also needs to do more to articulate implicit or explicit outcomes in current policy design, and assess how adaptation actions can be made more effective'. Hence researchers need to embrace rather than avoid the adaptation science–policy–implementation nexus and recognize that 'an improvement in resilience to climate change across the country requires more than publishing a set of documents' [42]. McDermott & Surminski [41] explore the interplay of climate risk assessment and normative decision-making at an urban level and show that, throughout any decision process, there are points where objective risk data meet subjective prioritization and normative judgements, and potentially controversy, for example, when setting 'acceptable risk levels' and identifying 'adequate' protection levels, which can lead to controversy over competing priorities and differing perspectives on what should be given precedence. Recognizing these intersections early is important for those who conduct the risk assessment as well as those who use it.

Several papers in this theme issue also refer to the rationale for public policy intervention and to ethical issues associated with risk. This highlights the increasing importance of linking climate change risk assessment with wider research on framing and communication of risk. This agenda would further position the conceptual and methodological innovations required beyond a conventional 'objective' risk assessment. It would recognize that risk is not an abstract concept but that it is necessarily subjective and strongly related to context, including attitudes to and tolerance for risk among different actors [67–69]. Such an agenda would be consistent with the wide diversity of contexts in which adaptation is taking place, including diverse perspectives on what is at stake in a changing climate. These perspectives are associated with divergent values and goals as, for example, associated with: the relative importance ascribed to the present versus future costs and benefits; on monetary against non-monetary risks; or on attitudes to average change compared to changes in extremes [70,71].

The most recent IPCC Fifth Assessment Report [22] has been the first to address how possible non-rational judgement and choice processes may interact with risk factors. A notable exemplar is use of heuristics in decision-making as a means to address risk complexity, information overload and bounded rationality; such heuristics may exhibit systematic biases related to risk perception (including loss aversion, cognitive myopia and preference for a *status quo* outcome). These perceptual issues may explain apparent paradoxes in adaptation when compared across different risks, including preferences for different types of adaptive response relative to risk type; social amplification of risk whereby perception can lead to overreaction [72]; or the reinforcement of maladaptive responses that purport to maintain the *status quo* as a 'low-risk strategy' [73], as has been suggested for aspects of insurance and flood risk management [74]. These complications highlight the crucial need for systematic collation and interpretation of different responses within assessment procedures to better understand residual risks and inform targeted policy interventions to reconcile residual risk with societal perceptions of tolerable risk.

In summary, climate change risk assessment is playing for high stakes when individuals, organizations, national governments and intergovernmental assessments seek to systemize and make sense of the climate change challenge. The papers in this theme issue demonstrate the variety of those risks and the fundamental interaction of the physical risk with the societal processes of prioritizing, avoiding harm and making legitimate decisions. Although there are universal elements to risk, based on individual and perhaps evolutionary traits of humans [7], the diversity of national-level climate risk assessment, in particular, demonstrates the role of the cultural differences and understandings, making clear the priority given to consequences, actions and the acceptability of non-action. Climate change at the global scale is in effect a planetary experiment with unforeseeable outcomes in which those in the position to influence the decisions are taking the risks and eschewing precaution.

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